PROJECT ID: EEMS020

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

# Energy Impact of Different Penetrations of Connected and Automated Vehicles

JACKELINE RIOS-TORRES

2017 U.S. DOE VEHICLE TECHNOLOGIES OFFICE ANNUAL MERIT REVIEW
JUNE 6, 2017

Argonne NATIONAL LABORATORY | INL Idaho National Laboratory | BERKELEY LAB | OAK RIDGE National Laboratory | NREL NATIONAL RENEWABLE ENERGY LABORATORY

# OVERVIEW

## Timeline

- Project start: October 2016
- Project end: September 2019
- Percent complete: 15%

## Barriers

- Barriers addressed
  - How to harness CAVs for reduced energy use in transportation

## Budget

- Total project funding
  - DOE share: 100%
  - Contractor share: 0%
- Funding received in FY 2016
  - $ 0
- Funding for FY 2017
  - $364K

## Partners

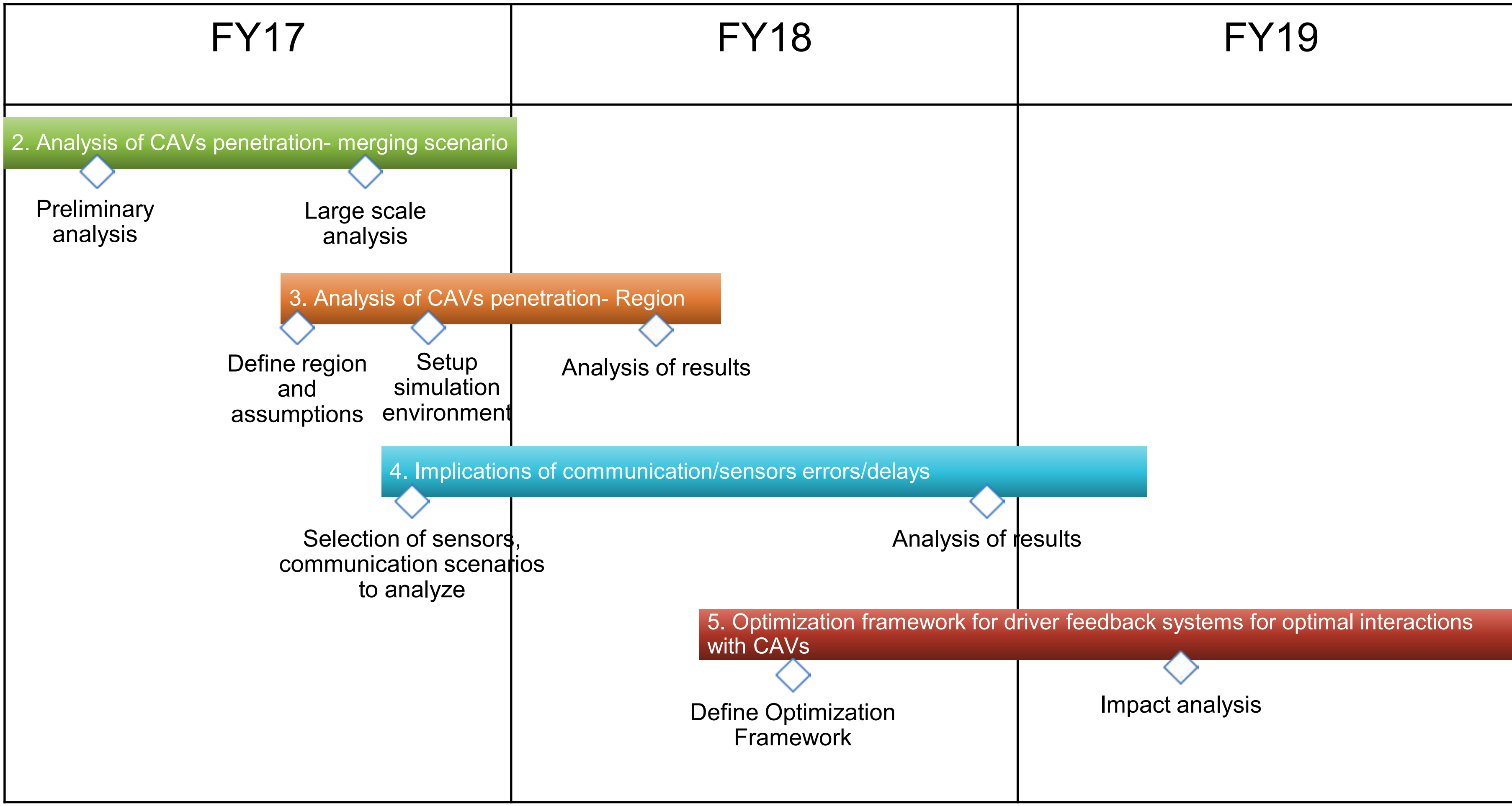
- Interactions/collaborations
  - SMART Mobility Consortia
- Project lead: Jackeline Rios-Torres

# RELEVANCE

- Objectives:
  - Explore the impact of different penetrations and levels of automation of connected vehicles on Energy and Mobility
  - Investigate the implications of delay/noise in the V2V or V2I communications on energy use and safety
  - Develop an optimization framework for driver feedback systems aimed at facilitating optimal interactions with CAVs
- Impacts:
  - Study the energy impacts of optimal control algorithms in CAVs and their operation in a mixed traffic environment

*Any proposed future work is subject to change based on funding levels*

# MILESTONES

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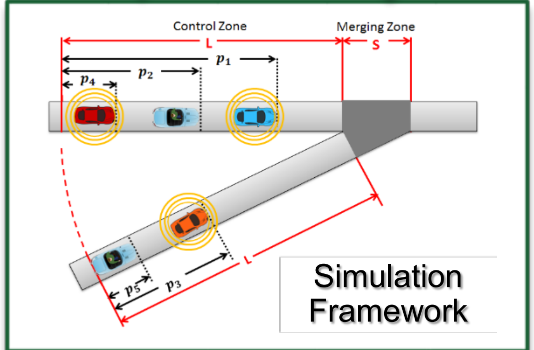
# APPROACH

- Subtask 1 FY17:
  - Implement the Connected and Automated Vehicles (CAVs) model
  - Implement the human-driven vehicles (HDVs) model and simulate baseline scenario (0% CAVs)
  - Develop a simulation framework in MATLAB (models integration) for a merging scenario
  - Define the traffic flow scenarios for evaluation
  - Evaluate the energy impacts of different penetration rates of CAVs under different traffic conditions

Connected and Automated Vehicles Model

Human-Driven Vehicles Model




Fuel consumption
Travel time

| Phase I | Phase II | Phase III |
|---|---|---|
| **CAVs + HDVs interactions** | **Sensitivity to communication/sensors errors** | **Optimal driver feedback systems** |

0 | 12 Months | 24 Months | 36 Months

*Any proposed future work is subject to change based on funding levels*

# APPROACH

- Subtask 2 FY17:
  - Integrate the Connected and Automated Vehicles (CAVs) model based on optimal control with a traffic simulator
  - Define the traffic flow scenarios for simulation
  - Simulate a baseline scenario for a particular region (0% CAVs)
  - Evaluate the energy impacts of different penetration rates of CAVs under different traffic conditions

| Phase I | Phase II | Phase III |
|---|---|---|
| **CAVs + HDVs interactions** | **Sensitivity to communication/sensors errors** | **Optimal driver feedback systems** |

0 — 12 Months — 24 Months — 36 Months

Connected and Automated Vehicles Model

Traffic Simulator

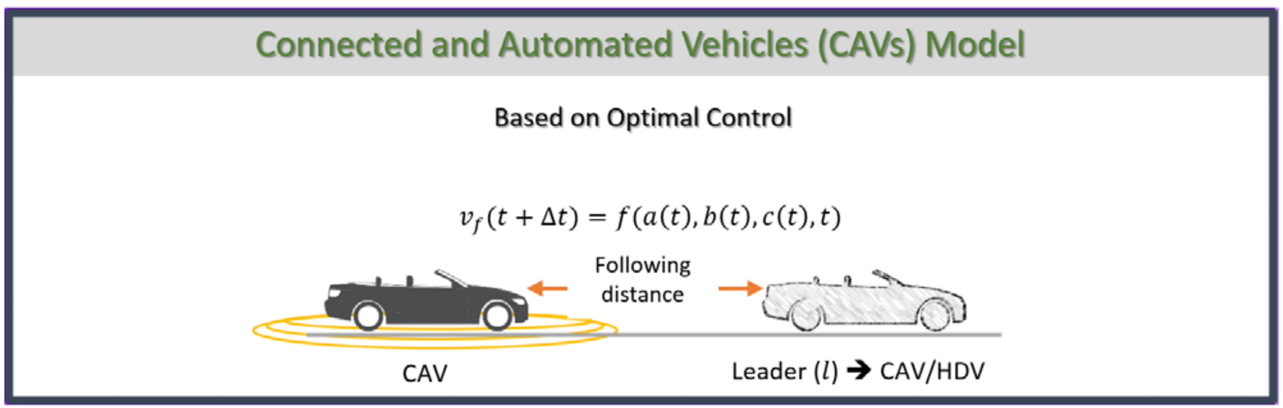
Fuel consumption
Travel time

*Any proposed future work is subject to change based on funding levels*

# TECHNICAL ACCOMPLISHMENTS (1)

- The CAVs model was implemented
  - Developed with the following specifics in mind:
    - Based on optimal control
    - Energy efficient
    - Implementable online
    - Closed-form

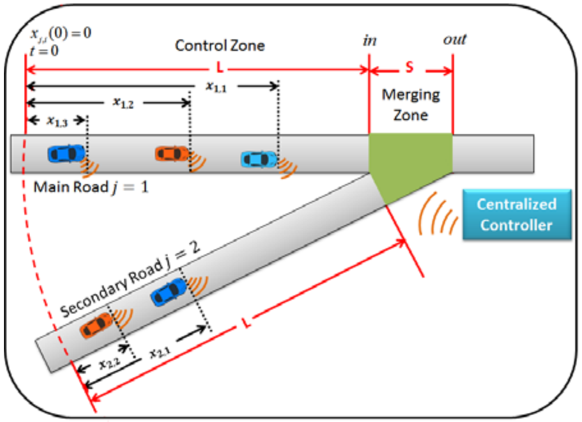
*We aim at coordinating the vehicles on the merging scenario while minimizing the energy consumption*



# TECHNICAL ACCOMPLISHMENTS (2)

We formulated the following optimal control problem*:

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \sum_{i=1}^{n} \int_{t_i^o}^{t_i^f} u_i^2 \, dt$$




Subject to:

Vehicle dynamics

$$\dot{p}_i = v_i$$
$$\dot{v}_i = u_i,$$

Safety Constraint

$$u_i \in R_i$$
$$R_i \triangleq \{u_i(t) \in [u_{\min}, u_{\max}] \mid p_i(t) \leq p_k(t) - \delta,$$
$$v_i(\mathrm{t}) \in [v_{\min}, v_{\max}], \forall i \in \mathcal{N}(t), |\mathcal{N}(t)| > 1, \forall t \in [t_i^0, t_i^f]\},$$

Where $R_i$ *is the control interval, δ a safe headway distance and* ***k*** *the leader of vehicle* ***i****.*

- We applied Hamiltonian Analysis to obtain the analytical solution for the unconstrained problem
- We obtain the optimal control input and states as a function of time and some unknown constants $a, b, c, d$:

$$u_i^*(t) = a_i t + b_i \longrightarrow \text{Optimal Acceleration}$$
$$v_i^*(t) = \frac{1}{2} a_i t^2 + b_i t + c_i \longrightarrow \text{Optimal Speed}$$
$$x_i^*(t) = \frac{1}{6} a_i t^3 + \frac{1}{2} b_i t^2 + c_i t + d_i \longrightarrow \text{Optimal Position}$$

* ***J. Rios-Torres*** *and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, April 2017. doi: 10.1109/TITS.2016.2587582*

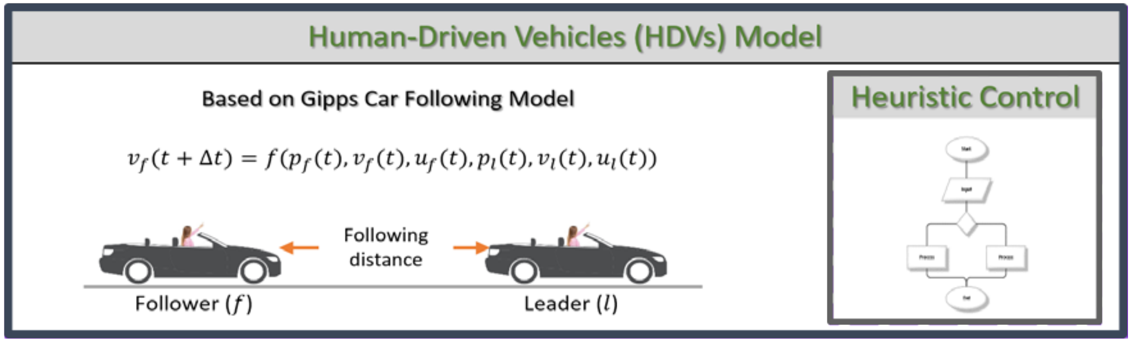
# TECHNICAL ACCOMPLISHMENTS (3)

- The HDVs model was implemented
  - The Gipps car following model is used to model the drivers' speed choices at each sample time.
  - It adjust the vehicle speed to keep a safe following distance from its leader vehicle or reach a desired speed in free traffic:

$$v_f(t+\ t\ ) = \min\{v_{f,acc}(t+\ t\ ), v_{f,dec}(t+\ t\ )\}$$

Where:

$$v_{f,acc}(t+\tau) = v_f(t) + 2.5u_{f,\max}\tau\left(1-\frac{v_f(t)}{v_{f,\max}}\right)\sqrt{0.025+\frac{v_f(t)}{v_{f,\max}}}$$ and, $$v_{f,dec}(t+\tau) = u_{f,\min}\tau + \sqrt{u_{f,\min}^2\tau^2 - u_{f,\min}\left[\begin{array}{c}2(p_l(t)-p_f(t)-(L_{veh}+fd)) \\ -v_f(t)\tau - \dfrac{v_f(t)}{\hat{u}_{l,\min}}\end{array}\right]}$$




$v_{f,acc}$ : free traffic speed
$v_{f,dec}$ : decreasing speed to keep safe distance from leader
$f, l$ : follower, leader
$p, v, u$ : vehicle position, speed and acceleration
$L_{veh}$ : vehicle length
$fd$ : desired following distance

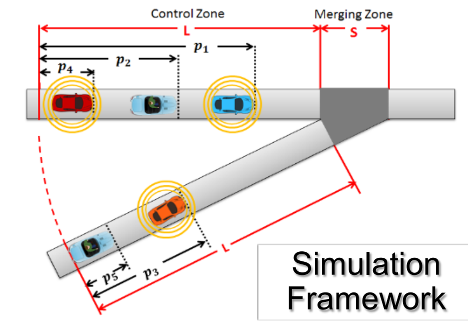
*The Gipps car following model aims at avoiding collisions with the leader vehicle*

# TECHNICAL ACCOMPLISHMENTS (4)

- Models were integrated to develop a simulation framework
  - Simulation set up:
    - Baseline: 30 HDVs on a merging on-ramp scenario
    - Desired speed HDVs : 13.41 m/s
    - Different penetration rates were explored:
      - 0%, 30%, 50%, 70%, 100%
      - CAVs were chosen randomly

Connected and Automated Vehicles Model

Human-Driven Vehicles Model



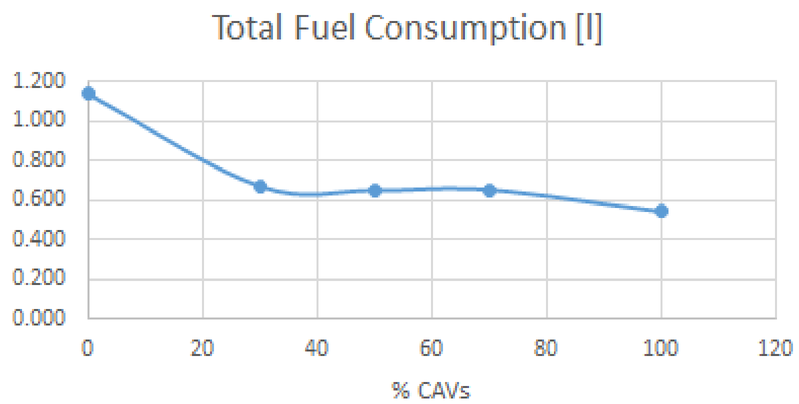

Simulation Framework

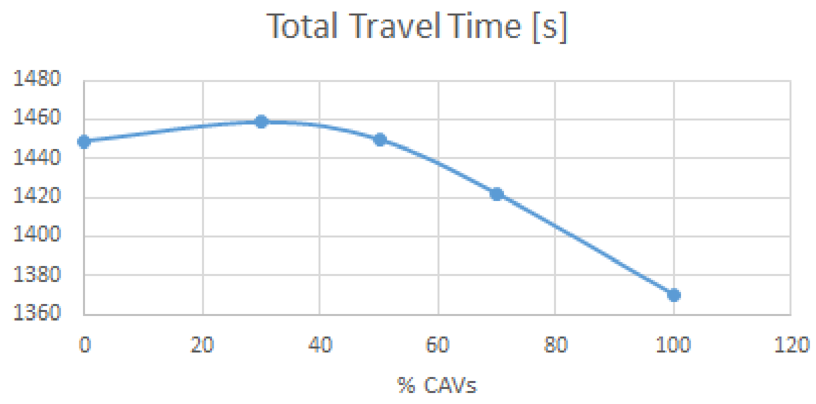
Fuel consumption
Travel time

# TECHNICAL ACCOMPLISHMENTS (5)

- The energy impacts of CAVs in mixed traffic were assessed for the simulated scenario
  - Using different penetration rates of CAVs, the simulation results indicate:
    - Low (30%) CAV penetration rates show significant fuel consumption benefits, but total travel time increase
    - Higher (70%) CAV penetration rates show significant reductions in total travel time and fuel consumption

***J. Rios-Torres** and A. A. Malikopoulos, "Energy Impact of Different Penetrations of Connected and Automated Vehicles: A Preliminary Assessment," ACM SIGSPACIAL Comput. Transp. Sci. 2016*

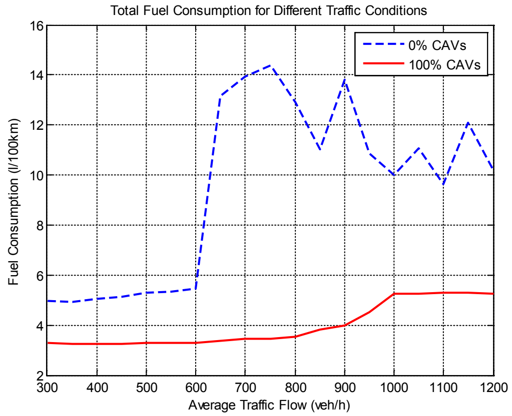


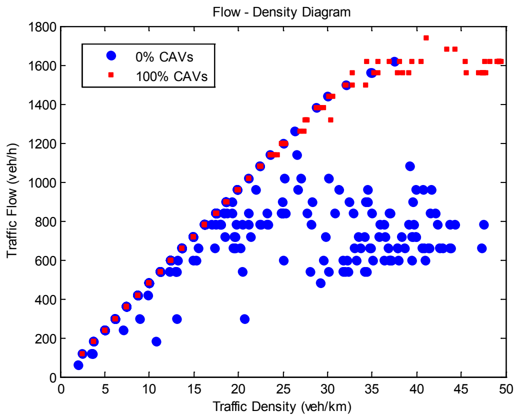



# TECHNICAL ACCOMPLISHMENTS (6)

- Ongoing work
  - Large scale study to assess the implications of CAVs under different traffic conditions. Preliminary results indicate:
    - CAVs can contribute to significant fuel consumption for diverse traffic conditions under average and high congestion scenarios
    - CAVs allow for more stable traffic patterns even for high density traffic

***J. Rios-Torres** and A. A. Malikopoulos, Impact of Connected and Automated Vehicles on Traffic Flow (In preparation)*



# RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

- N/A (Project started October 2017)

# COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- SMART Mobility Consortia:

Argonne National Laboratory · NREL National Renewable Energy Laboratory, Innovation for Our Energy Future · Berkeley Lab, Lawrence Berkeley National Laboratory · INL Idaho National Laboratory

- University Collaboration:

University of Delaware · Boston University · The University of Tennessee Knoxville

# REMAINING CHALLENGES AND BARRIERS

- Integration of the CAVs and HDVs in a traffic simulator

- Definition of appropriate driver incentives require additional analysis of driver behavior and decisions

# FUTURE WORK

- Ongoing
  - FY17: large scale analysis of the implications of different CAVs penetration rates on a merging scenario
  - FY 17: analysis of the implications of different CAVs penetration on a highway corridor
- Proposed
  - FY18: Explore sensitivities in CAVs performance to communication/sensors errors and delays
  - FY 19: Develop a driver feedback system for optimal interaction with CAVs

*Any proposed future work is subject to change based on funding levels*

# SUMMARY

- **Relevance:** study the energy impacts of optimal control algorithms in CAVs and their operation in a mixed traffic environment
- **Approach:** develop a simulation framework combining a human driver model and a CAVs model based on optimal control.
- **Collaborations:** Smart Mobility Consortium
- **Technical Accomplishments:**
  - Using different penetration rates of CAVs, the simulation results indicate
    - Low (30%) CAV penetration rates show significant fuel consumption benefits, but total travel time increase
    - Higher (70%) CAV penetration rates show significant reductions in total travel time and fuel consumption
  - J. Rios-Torres and A. A. Malikopoulos, "Energy Impact of Different Penetrations of Connected and Automated Vehicles: A Preliminary Assessment," ACM SIGSPACIAL Comput. Transp. Sci. 2016
- **Future Work:**
  - Large scale analysis
  - Study the implications of vehicle communication and sensors errors on the performance of a transportation system
  - Develop driver feedback system for optimized interaction with CAVs

*Any proposed future work is subject to change based on funding levels*

# QUESTIONS?

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